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Introduction: The U.S. Army Corps of Engineers makes extensive use of modern instrumentation for measuring the behavior of large structures. One of these instrumentation programs is high precision geodetic surveying. This type of surveying, accomplished through the use of classical trianulation and/or trilateration techniques, provides a reliable measure of displacement as a function of time. Typically, accuracies of 5-10 mm can be achieved. Final accuracy of the displacement is a function of many factors, including: network geometry, field procedures, survey crew experience, and equipment.

Unfortunately, the high precision geodetic survey is a labor intensive endeavor, and thus time consuming and rather expensive. For this reason, surveys are made infrequently, normally at 6- to 18-month intervals, or sometimes not at all unless there is a suspicion of structural distress.

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There are several major requirements for an automatic monitoring system:

a. Points on the structure (object points) should be measured relative to stable moum
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b. The relative precision of the measurements should be on the order of 5 mm over distances as large as 5 km.

c. Measurements should be made on a continuous basis with a period of about 1 to 3 hours.

d. The system should operate with little attention from personnel. The system should not require a highly skilled operator at any time other than for installation or maintenance.

e. The system should be easy to install and have low maintenance requirements.

f. The system should be reliable.

g. The final cost-per-point-measured after considering all operations, maintenance and installaiton costs should be compatible with, or less than, that provided by conventional techniques.

With the deployment of the Navigation Satellite Timing and Ranging (NAVSTAR) Global Positioning System (GPS), a possibility for continuous, automatic monitoring of structures has materialized. Precise, relative measurements of object points, meeting the above criteria, are possible using GPS.

The primary object of this paper is to outline the applicability of the GPS to structural deformation monitoring. Preliminary designs of the hardware and software for an automated system will be presented along with the results of recent repeatability tests.

CONTINUOUS DEFORMATION MONITORING
WITH GPS[a]

By Stephen R. DeLoach[1], M. ASCE

INTRODUCTION

The U.S. Army Corps of Engineers makes extensive use of modern instrumentation for measuring the behavior of large structures. One of these instrumentation programs is high precision geodetic surveying. This type of surveying, accomplished through the use of classical triangulation and/or trilateration techniques, provides a reliable measure of displacement as a function of time. Typically, accuracies of 5-10 mm can be achieved. Final accuracy of the displacement is a function of many factors, including: network geometry, field procedures, survey crew experience, and equipment.

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[a]Presented at the May 11-14, 1988, ASCE Specialty Conference, GPS-88 Engineering Applications of GPS Satellite Surveying Technology held in Nashville, TN.

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GPS DESCRIPTION

The GPS is a satellite navigation, timing, and ranging system developed by the U.S. Department of Defense (DOD). It is being implemented and operated by the U.S. Air Force. The system was designed to provide continuous, all-weather navigation anywhere in the world. It consists of three segments: the space segment (or satellite constellation), the control segment (or the ground facilities), and the user equipment.

The space segment will consist of a satellite constellation with 18 satellites in 6 orbits at an altitude of about 20,000 km. The orbital planes will be inclined at 63 degrees to the equator. Additionally, there will be three spares in orbit. This configuration will ensure that four satellites are always in view, therefore providing 24-hour, worldwide coverage.

Presently, there are seven operational satellites in orbit. These are experimental "Block I" satellites which will be progressively replaced with the full constellation of operational "Block II" satellites. The Block II satellites were to be placed in orbit by the Space Shuttle between 1986 and 1989. To overcome delays in the Shuttle Program, the U.S. Air Force has awarded a contract for the construction of 20 Medium Launch Vehicles. These rockets will allow the Block II satellites to be in orbit by the early 1990's.

The existing constellation of satellites has been set up to provide the optimum orbital geometry for system testing over North

America. On any given day, the satellites are in view providing a "window of opportunity" for about 4 hours. This 4-hour window regresses each day by about 4 minutes.

Each satellite transmits navigation signals on two L-Band frequencies: L1 at 1575.4 MHz and L2 at 1227.6 MHz. These L-Band frequencies, or carrier waves, have wavelengths of about 19 and 24 cm, respectively. Modulated onto these carrier waves is a Data code, or navigation message, containing clock parameters, the satellite ephemerides, and other general system information. The Precise (P) code is also modulated onto both the L1 and L2 carrier waves. The Course/Acquisition or C/A code is modulated on the L1 carrier only.

The control segment of the system consists of a series of ground stations. These stations track and monitor all satellites in view. From the tracking data, the satellite status is monitored and precise orbit computations are performed. Based on the actual "precise" orbit computed after the fact, a daily orbit "prediction" is made. This information is uploaded on a daily basis into each satellite to be transmitted with the navigation message as the "broadcast ephemeris."

The final segment of the GPS is the user equipment. There are a number of different receivers available on the market today. However, they all receive the same basic satellite information; therefore, it is more appropriate to discuss the types of measurements available with the GPS.

Measurements of position can be made with the GPS using the P or C/A code. A single measurement from any satellite based on either code is referred to as a "pseudo-range." A pseudo-range is simply the distance measurement from the satellite to the receiver antenna plus some unknown error. Assuming the satellite positions are known, based on the broadcast or precise ephemeris, the 3-dimensional position of the receiver antenna and the receiver clock offset can be computed at any single epoch where four satellites are observed simultaneously. The use of this type of measurement is termed the Precise Positioning Service (PPS) when using the P code, and the Standard Positioning Service (SPS) when using the C/A code. At present, the positional accuracy of this technique is about 15 meters with either code. The DOD has announced the antispoofing or encryption of the P code, thus making it available for select users only. It was also the DOD's intent to create a Selective Availability, or to dither the C/A code, to degrade its positional accuracy to about 100 meters. However, this issue has not been resolved completely.

It is also possible to compute a receiver's position by processing carrier phase measurements. This technique involves tracking the L1 or L2 carrier signal, or both. State-of-the-art receiver electronics will allow the signal phase to be measured to an accuracy of about 1 mm. However, the measurements are ambiguous because the whole number of cycles from the satellite to the receiver is unknown (integer cycle ambiguity). By recording simultaneous observations at multiple stations, sophisticated signal differencing techniques may be employed. These techniques allow 1) the elimination of several error sources and 2) the resolution of the integer cycle ambiguity. The result is a 3-dimensional baseline determination between two receivers. The accuracy of this measurement is at the 1- to 2-part-per-million (ppm) level for baselines less than 50 km in length. On a 1-km baseline, 1 ppm would equal 1 mm. These accuracies have been documented through extensive field tests (Hothem & Fronczek 1983). Knowledge of the P code is not required. Any future degradation of the C\A code should have little or no effect on the accuracy of baseline determinations using this technique.

BASELINE AND DEFORMATION VECTORS

For structural monitoring applications, the precise carrier wave measurements are required as previously described. The resultant of these measurements is the three-dimensional baseline vector V between two stations measured at a single epoch, i, where:

$$V_{i} = (\overset{\text{delta}}{\Delta} X_{i}, \Delta Y_{i}, \Delta Z_{i}) \tag{1}$$

The deformation vector, D, is computed by differencing between two epochs i and j at a single station.

$$D_{ij} = (\overset{\text{delta}}{\Delta} X_{i} - \Delta X_{j}, \Delta Y_{i} - \Delta Y_{j}, \Delta Z_{i} - \Delta Z_{j}) \tag{2}$$

The standard error of each component of the baseline vector at any epoch is given by

square root

$$\text{Sigma} — \sigma_{V} = \sqrt{a^2 mm + b^2 mm/km} \qquad \text{b squared} \tag{3}$$

a squared

where:

a is a constant error and

b is an error proportional to the length of the baseline.

sigma

The standard error σ_{V} may be assumed (a priori) based upon previous experience and testing, or computed after the fact where redundant observations are available (a posteriori). In the case of a posteriori computations, least squares adjustment algorithms are required to generate the appropriate variance-covariance matrix containing the standard errors in the "X", "Y", and "Z" planes.

The standard error of the deformation vector is then approximated by

square root

$$\text{Sigma} — \sigma_{\Delta} = \sqrt{2}\ \sigma_{V} \tag{4}$$

ERROR SOURCES

There are a number of error sources which can degrade a baseline solution. These may be divided into three general categories:

a. instrumentation errors

b. modelling errors

c. computational errors.

The instrumentation errors are the most varied. The major contributing sources are: oscillator variations at the satellite and receiver station, signal multipath, antenna collimation, and antenna height measurement. The oscillator, or clock, errors may result from an offset from Coordinated Universal Time (UTC), offset between receiver stations, variations in drift, or simply the limit of the clock stability. These variations can easily result in positional errors of several meters. Signal multipath is caused by reflection of the signal from the ground or surrounding objects before reaching the antenna. The effects of multipath on the observed phase is a function of the surrounding physical features, antenna installation, and antenna design. The magnitude of this effect is generally limited to several centimeters (Young 1985). Councilman (1981) has suggested it can be reduced to several millimeters with proper antenna design. Additionally, King et al. (1985) state that the period of multipath when using tripod-mounted antennas is only a few minutes, allowing some averaging to occur over long observation spans. Antenna collimation errors are a result of improper placement of the antenna over the desired station. Likewise, height measurement errors actually reflect the precision of the operator's ability to physically measure the vertical distance from the station mark to the antenna.

The second category of error is comprised of modelling errors of the actual satellite orbits and the propagation medium. All GPS computations are ultimately based on the orbital position of the satellites at the time of signal broadcast. These positions can be estimated from either the "precise" or "broadcast" ephemeris. A baseline vector will be roughly in error by the ratio of the satellite orbital error divided by the satellite altitude. GPS signals must travel through the earth's atmosphere and thus encounter delays in the troposphere and ionosphere. Propagation delays created by the troposphere can be modelled by monitoring the temperature, pressure, and relative humidity at a station. Doing so will maintain a baseline error of about 1-ppm. Ionospheric refraction can amount to a 1- to 5-ppm error in the baseline vector if making observations with a single frequency instrument. This effect can be essentially eliminated by using a dual frequency (L1 and L2) receiver. Each of these modelling errors has been found to be highly correlated for short baselines. Therefore, in structural monitoring applications they will tend to cancel out if the appropriate processing techniques are used and baselines are limited to a few kilometers. For longer baselines, it may be necessary to monitor both the L1 and L2 frequencies and to utilize a "precise" ephemeris.

The computational errors result from the inability to resolve the integer cycle ambiguity (the whole number of wavelengths between satellite and station). Once a receiver has acquired a satellite signal, the whole number of cycles are tracked and counted. Therefore, the initial, or unknown, integer cycles will remain the same throughout an observing session and can be represented by a single bias term. This problem is further compounded if loss of lock, or a cycle slip, occurs, thus adding some unknown number of whole cycles. Typically, the integer cycle bias values are estimated with a least squares fit along with the baselines between stations. Generally, the solution for the bias estimates will not be integer values. Therefore, they are rounded to the nearest integer and the least squares solution repeated. The final, or "best," solution is then chosen based on the application of statistical tests of the integer bias parameters.

The primary solution for most of the errors mentioned is careful selection of post-processing techniques. The most popular method involves <u>signal differencing</u>. This method can be thought of as simply subtracting observed signals between stations, satellites, epochs, or any combination of these. For geodetic quality applications, the carrier phase observables are differenced.

A technique known as <u>double differencing</u> involves differencing of simultaneous carrier phase observations between: 1) stations and 2) satellites. The benefit from this solution is the cancellation of errors from station and satellite oscillator instabilities plus elimination of errors from orbital modelling and atmospheric modelling errors on short baselines. Some of the versions of post-processing software released within the past several months also include strong statistical testing of the integer cycle bias parameters. This is extremely valuable in assuring the correct selection of the integer bias and in overcoming loss of lock on the satellite signal.

TESTING

In September 1986, the U.S. Army Engineer Topographic Laboratories (USAETL) purchased six TRIMBLE Model 4000S GPS receivers with associated antennas, data logging and post-processing hardware and software. More recently, this equipment has been upgraded to include 10 tracking channels, more stable micro strip antennas, internal data logging, and enhanced post-processing software. This equipment will be used as the basis for an automated deformation monitoring system. To establish an a priori estimate of the positional standard error that can be achieved with this system, extensive field testing was conducted during March, April, and May 1987.

The testing was conducted at a facility of the National Geodetic Survey (NGS) located at Corbin, VA. At this facility, the NGS has established a test quad for testing and evaluating a variety of surveying instruments. Each station consists of a monument constructed of concrete poured in place on undisturbed earth. Each monument protrudes 5 cm above the ground surface and extends 1.5 meters deep. Monuments are 45 cm in diameter at the bottom and taper to 25 cm square at the top. There is a bronze disk set in the top of each monument, and the point of reference is a 0.4-mm diameter hole drilled in the center of each disk. Each monument has a permanent wooden stand built over it. The stand is fitted with a specially designed adjustable tribrach with a 1.9 cm diameter hole in the center.

Before occupying each station, the adjustable tribrach was collimated using a WILD NL optical plummet. Next, a WILD GDF 6 type tribrach was fastened to the adjustable tribrach with a specially machined bolt which force centers the alignment between the two tribrachs. The receiver antenna was then mounted in the GDF 6 tribrach for the observation session. The NL optical plummet was used again after the session to verify the stability of the stand and adjustable tribrach during the observing period. The height of each tribrach was also measured before and after each session. This procedure limits the standard error in horizontal and vertical positioning of the antenna to about 0.5 mm.

The test quad was originally observed with a Geodimeter 112 Electronic Distance Meter, a WILD T-3 theodolite, and a Zeiss NI 002 level. These data were adjusted by NGS with the HAVAGO 3-dimensional adjustment program written by Vincenty (1979). Based on this adjustment, the horizontal accuracy of the quad is at the 2-mm level; the vertical accuracy is at the 1-mm level.

Data were collected on a total of 6 baselines where each line had from 2 to 12 days of observations. A total of 33 independent baselines were observed and processed, providing daily observations
delta
of ΔX, ΔY, ΔZ and the 3-dimensional baseline vector, or distance. Also, the difference between the GPS baseline distance and the original

adjusted network values was computed. Additionally, the mean and standard deviations of each baseline were computed where:

the sample mean is

$$\bar{X} = \frac{1}{n} \sum_{i=1}^{n} X_i \tag{5}$$

and the standard deviation of a single observation is

$$\sigma_X = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (X_i - \bar{X})^2} \tag{6}$$

sigma

where X_i is the ith observation and n is the number of observations.

By computing the mean of all the differences between the GPS baselines and the original network values, the accuracy of the system was found to be about 0.3 mm. However, a better description of the system is shown by computing the mean of the standard deviations of the ΔX, ΔY, and ΔZ components. This computation results in a level of precision, or repeatability, at the 4.2-mm level. The level of ability to detect deformations would then be estimated according to equation 4 as 5.9 mm.

delta

AUTOMATIC CONTINUOUS OPERATION

The potential for an automatic and continuous monitoring system (CMS) for structural deformation studies exists with the GPS technology available today. However, additional software must be developed and hardware installations must be carefully designed to link the various pieces of equipment and to minimize potential error sources.

Existing techniques to determine extremely precise baselines require observations be recorded at each of two stations simultaneously. Each set of observations should also be about 1-hour in duration. The data tapes must then be collected for post processing on a computer similar to an IBM PC-AT. A 1-hour observation span normally requires approximately 30 minutes post processing for each baseline, although active CPU time is only about 10 minutes. When more than two receivers are operated in the field, the number of independent baselines measured is n-1, where n is the number of receivers; likewise, the time required for post processing would be (n-1) X 30 minutes. When post processing these lines, careful attention must be given to file maintenance. Present GPS operating systems typically do not include any file management procedures or software. Therefore, the burden of file management lies solely with the system operator. Further data analysis beyond baseline processing also requires the system operator to use his own methods or to adopt techniques from sources other than GPS manufacturers. Additionally, to log data the operator must set up appropriate files and instruct the receiver on appropriate satellites, tracking times, and other miscellaneous station information.

To create an automatic system, software must be developed to link together the various steps from planning an observation session to data logging to post processing and data presentation. The routines must also be interactive within themselves to allow data collection at the receivers while the previously collected baselines are being computed and analyzed.

To facilitate the software development, an existing library of programs is presently being built into a larger interactive group. This group of programs will be driven by a central program.

The system design calls for several features. The first is that a deformation study will be divided into segments of time called "epochs." For data processing, the assumption is made that during any one epoch there will be no structural movement. Because the satellite observations are made in the static mode, the minimum length of an epoch is the minimum length of time required for accurate satellite measurements (about 1/2 to 1 hour), and the maximum length of an epoch is the longest available period of continuous visibility of a minimum of 4 satellites (about 3 to 5 hours). A preliminary analysis of computer loading requirements has set the design epoch to between 1 and 4 hours, with the upper limit being constrained by a maximum daily raw data volume of 150 megabytes and the lower limit being constrained by the time required to download and process data from each epoch. Within this restriction, the length of an epoch and the interval between epochs are user defined. The interval between epochs is defined as the period of time between the beginning of one epoch and the beginning of the next epoch. Station coordinate computations for an epoch will use a constellation of all available and healthy satellites to compute a unique solution.

Another feature is the system's automatic operation. The system is designed to operate with a minimum of user interaction. Except for system start up and the weekly replacement of an archive tape, no user interaction should be necessary. Furthermore, the system is designed to recover automatically from a wide variety of failure conditions. Finally, this system is capable of operating with a network of 10 receivers.

The final system will consist of three to ten TRIMBLE Model 4000 SL receivers (modified to operate with the CMS software), the CMS software, and two personal computers with associated printers and plotters. When operating, two receivers will be on stable reference stations. All remaining receivers, up to eight, will be at object stations on the structure.

The final result of the data collection and processing is the deformation analysis. This will involve a least squares adjustment of observations and coordinates together with a statistical analysis and testing of the resulting vectors. This software is still in the developmental stages, and a complete treatise is not possible at this point; however, the philosophy is to perform a combined adjustment between epochs. Each baseline computed with the TRIMVEC software with its associated variance-covariance matrix and an a priori estimation of errors based on the reference station positions will be adjusted in combination with the comparable information from another epoch.

The output of the analysis will be in both tabular and graphic form, and will be of two types. The first is the vector of apparent movement as computed from the most recent epoch compared to the base, or original, epoch. The vector will be plotted along with its error wedge and the station coordinate error ellipse, and will appear similarly to that shown in Fig 1. This information will be provided in real time or may be displayed from available files after the fact.

The second type of output is movement over time and will be represented by a time plot of the movement vectors from numerous epochs compared against the base epoch. This information will only be available by user request. Both output types will be available at the project site or at any site, such as a district office, by using a third computer and a telephone modem.

The primary on-site hardware requirements, in addition to the GPS equipment, are two personal computers operating separately but linked together. Each computer (PC1 and PC2) will operate in a continuously looping cycle of epoch observations and processing (see Fig. 2). PC1 will be responsible for system monitoring, receiver status, satellite data collection, and baseline processing. At the end of each epoch, it will instruct each receiver to end the current observing session and begin a new one, and will download the previous session's data from the receivers while they are in the present measurement cycle. Next, PC1 will assess the data for quality and reliability, and process each independent baseline to determine its three vector components and the associated error estimates. Finally, PC1 will complete all data logging and file maintenance under its responsibility. One such cycle will be completed for each epoch in real time.

The second computer, PC2, also completes tasks during each epoch. Of primary importance is the combination of the most recent epochal data from PC1 with the data of the base epoch, and the performance of a combined least squares adjustment of the two epochs. The adjusted results are then used to report on apparent movement of the object stations between the current and base epochs. In addition, PC2 will be available for user interaction. It will provide a menu for data review and custom deformation analysis, and will be responsible for the original system definition and automatic data archiving.

A third computer, PC3, will allow an individual at a remote location to access the continuous monitoring system through a telephone modem to download data and to run processing routines similar to those on PC2. This will allow an engineer at headquarters to access and review the operation at any number of sites being monitored.

Although a tremendous amount of new software and hardware is being developed, the observing schemes, baseline processing, and data analysis will remain similar to those presently used for geodetic surveying. This should result in an overall positional accuracy of about 6 mm as previously reported.

To ensure the highest possible accuracy, the system hardware must be designed and constructed to minimize any potential errors. These errors would be a function of:

a. signal multipath

b. electrical interference at receiver and data link

c. antenna collimation

d. antenna height

e. reference point stability

f. object point stability.

Preliminary testing indicates that the hardware may be configured similarly to that shown in Fig. 3. The data links may be completed by either fiber optics or dual twisted pair wire (telephone line) with RS232 and/or telephone modem communications switches. For antenna separation of more than a few kilometers, radio communication may be necessary. However, for structural deformation monitoring the units are generally within a small area. Therefore, dual twisted pair wire or fiber optics are the natural choice; radio links have not been considered in the present design. The primary consideration in choosing between fiber optics or twisted pair wire is the subjection to electrical interference along the cable route. If the cable is run through existing lighting conduit or is on a power generating facility, the more expensive fiber optics may be necessary to prevent signal degradation. On a longer cable run, such as to a reference point, it may be possible to avoid interference areas and use the inexpensive twisted pair wire.

Testing of both the dual twisted pair wire and the fiber optics was conducted during the repeatability testing. Both links operated satisfactorily.

Signal multipath will be reduced by careful selection of each antenna site. Each station will be chosen to minimize signal reflection from surrounding objects, primarily hard surface walls. Another critical consideration for the selection of station location is line of sight to the satellites. For the GPS to operate, there must be clear line of sight between the receiver antenna and each satellite being tracked. This location selection may be accomplished with the aid of a satellite visibility diagram (see Fig. 4). Note that in this example an azimuth of 290° degrees from the station would be of concern because of its potential to block line of sight to satellite nos. 9, 11, 12, and 13.

Antenna collimation and height measurement errors will be reduced by incorporating a forced centering device (see Figs. 5 and 6). This device is designed such that each time a survey target or GPS antenna is placed on the station it will be forced into the exact position previously occupied in both the horizontal and vertical planes. The stability of the reference points and object points are a function of their construction and location. Suggestions for their construction are given in Fig. 7.

DEMONSTRATION PROJECT

The developmental stage of this project is scheduled for completion in September 1988. System testing and debugging will begin immediately with a full system demonstration scheduled for November 1988 through February 1989.

The demonstration system will be installed at the U.S. Army Corps of Engineers Dworshak Dam project on the North Fork of the Clearwater River near Orofino, Idaho. This structure is the highest straight-axis, concrete gravity dam in the western world and the largest ever constructed by the Corps. The height of the dam, foundation to crest, is 218 meters. This project is a vital unit in the comprehensive development of the water resources of the Columbia-Snake River drainage area.

The demonstration system will consist of six TRIMBLE model 4000 SL receivers. Each of these receivers has been upgraded to 10 independent tracking channels. Four of the receiver antennas will be placed on object stations along the crest of the dam. The receivers will be placed in the uppermost gallery, just below the roadway along the crest (see Fig. 8). The total separation of the antennas, monolith 19 to monolith 28, will be about 150 meters. The monoliths were selected because they are the highest in the structure and also contain other instrumentation for correlating measurements.

Each receiver will be supplied with AC power, and a fiber optics cable will be used as the data link from the receivers to a multi port data switch (see Fig. 9).

Another fiber optics cable will run from the data switch in the gallery to PC1 operating in the powerhouse at the base of the dam (about 180 meters vertical and 180 meters horizontal). The remaining two receivers will be placed on stable reference sites. One is about 3 km downstream of the dam and the other about 1.5 km upstream. Each of these units will be installed in a secure building with AC power and telephone lines. Auto-dial modems and telephone lines will be used to transmit information and data between these receivers and PC1 (see Fig. 10).

The computing system, PC1, PC2, printer, plotter, and all peripherals will be located in an office in the powerhouse. Full power and communications links will be provided to each PC. Finally, PC3 will be located 4000 km away, in the junior project engineer's office located at USAETL, Fort Belvoir, VA.

CONCLUSION

The NAVSTAR Global Positioning System has the potential to be used in an automatic mode to continuously monitor structural deformations. During the next few months, a system will be developed to operate such a system. It will then be installed at the U.S. Army Corps of Engineers Dworshak Dam for demonstration.

Testing of presently owned government GPS equipment indicates the system will detect movements of about 6 mm in three dimensions if reference points and object points are within a few kilometers of each other.

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Any use of trade names and trademarks in this publication is for identification purposes only and does not constitute endorsement by the U.S. Army Corps of Engineers.

APPENDIX I.--REFERENCES

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APPENDIX II.—NOTATION

The following symbols are used in this paper:

V_i = the three-dimensional baseline vector at epoch i

delta ΔX_i = the X component of the baseline vector at epoch i

ΔY_i = the Y component of the baseline vector at epoch i

ΔZ_i = the Z component of the baseline vector at epoch i

D_{ij} = the deformation vector found by differencing between epochs i and j

Sigma σ_V = standard error of the baseline vector

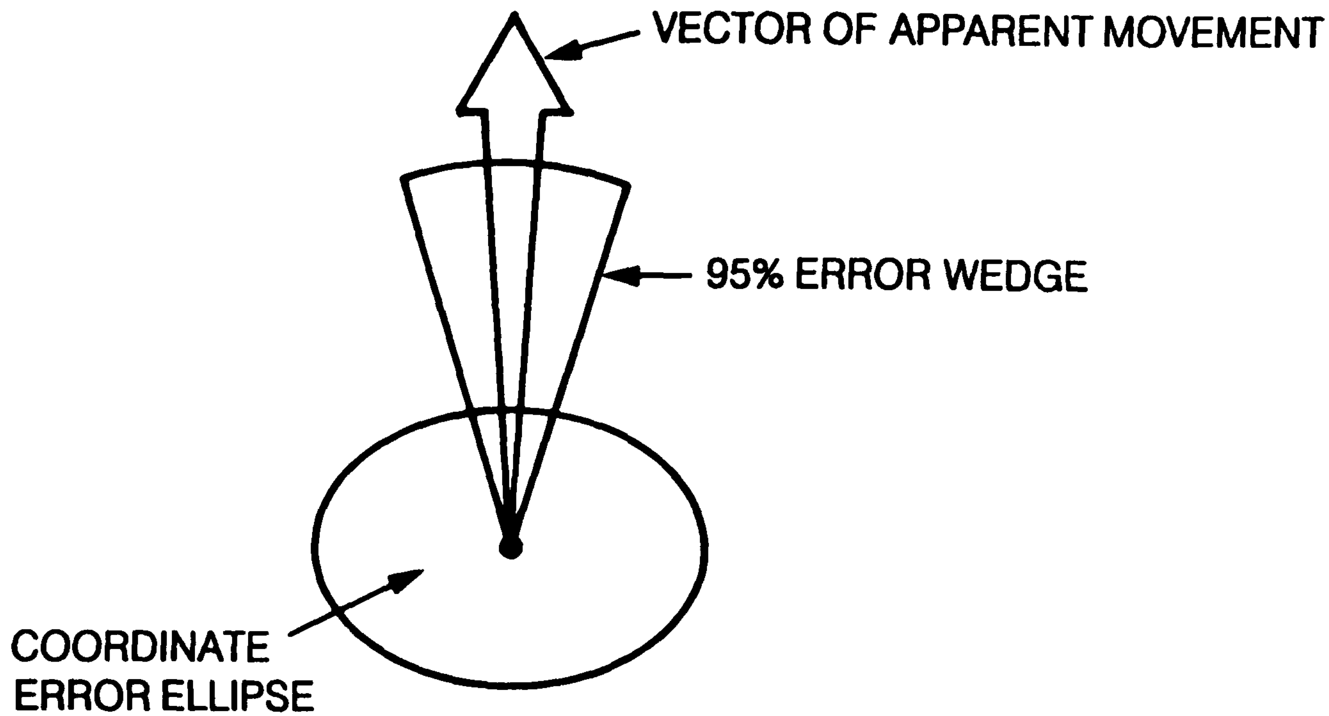
σ_D = standard error of the deformation vector

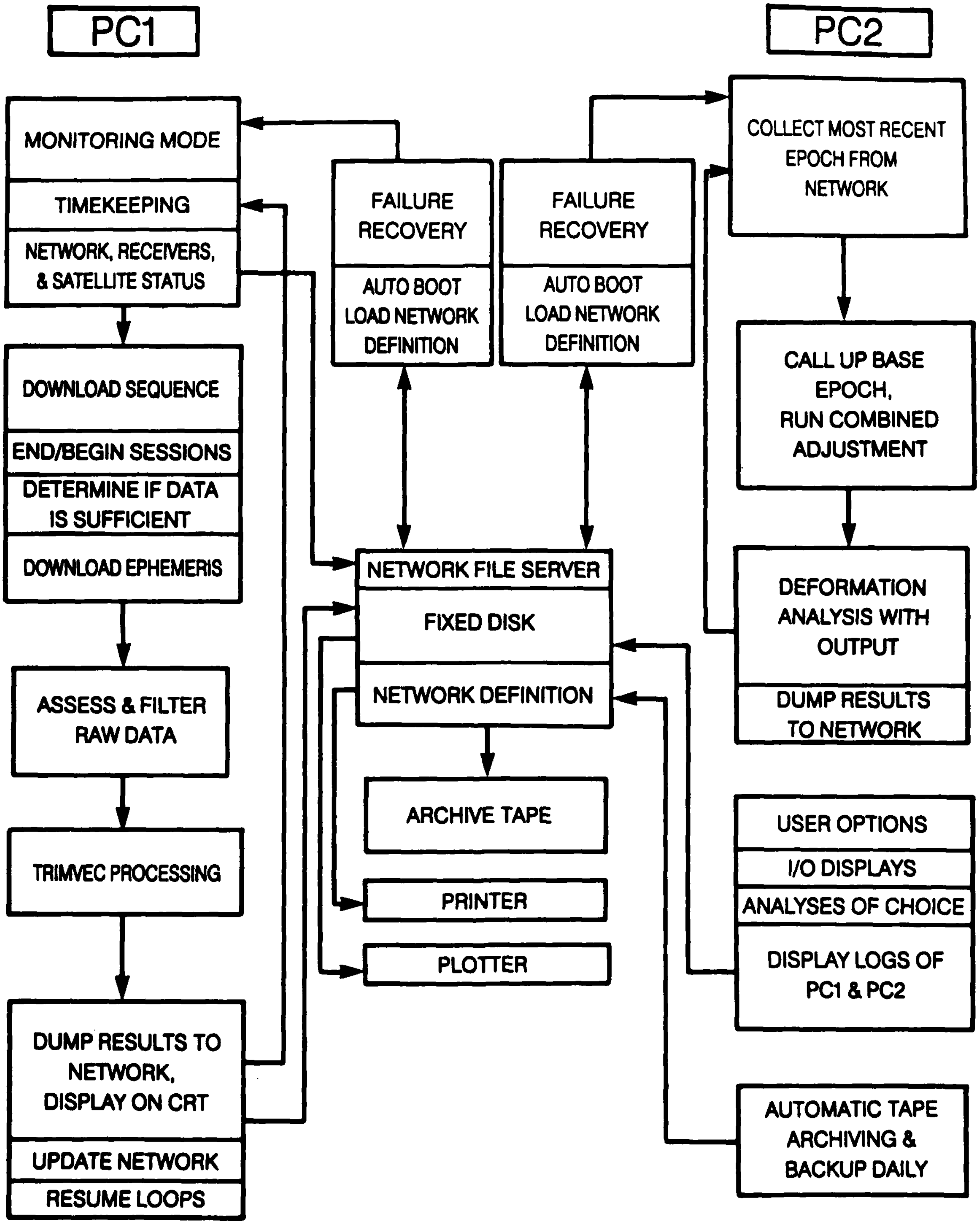
$\bar{X}$ = sample mean

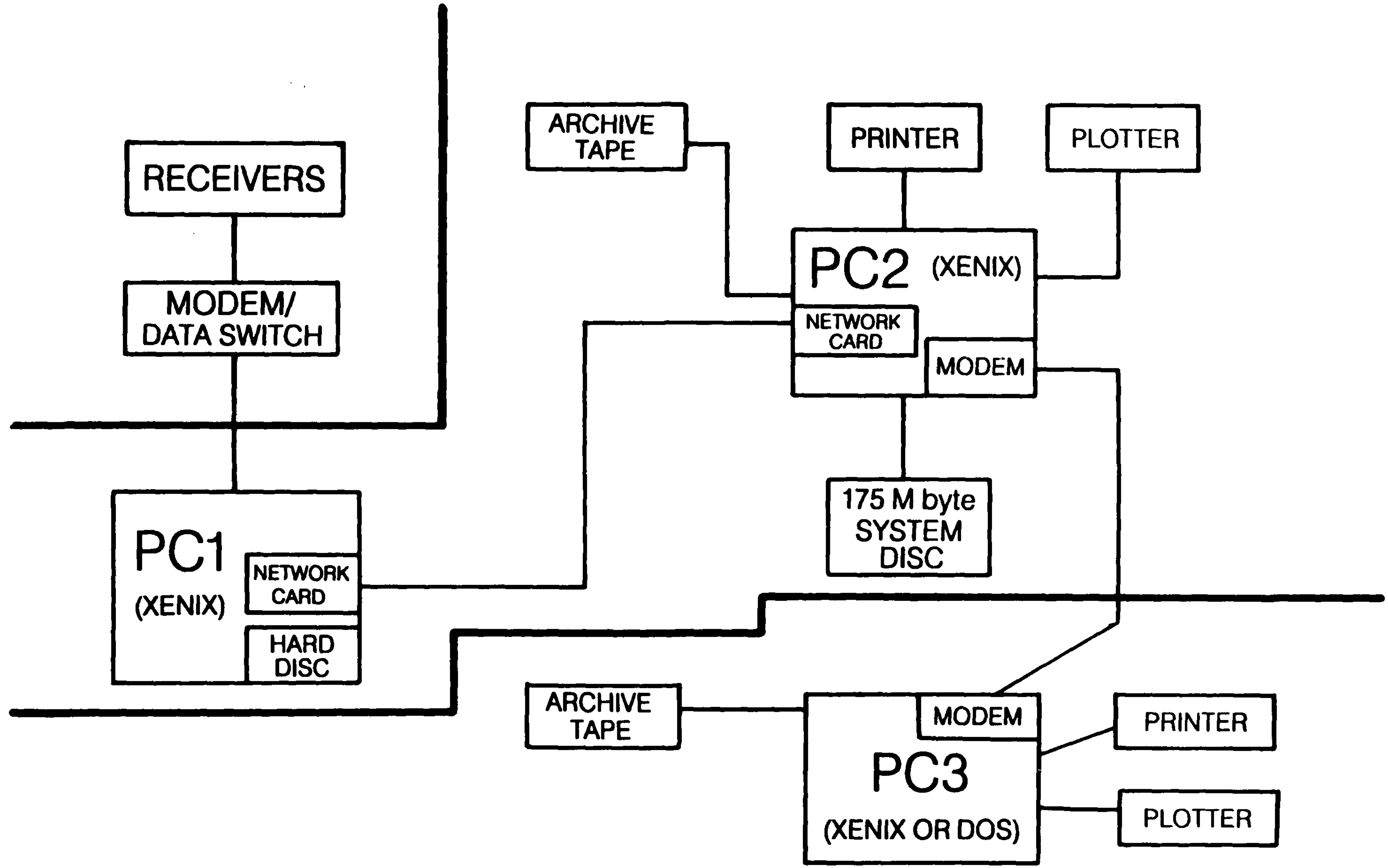
σ_X = standard error of a single observation

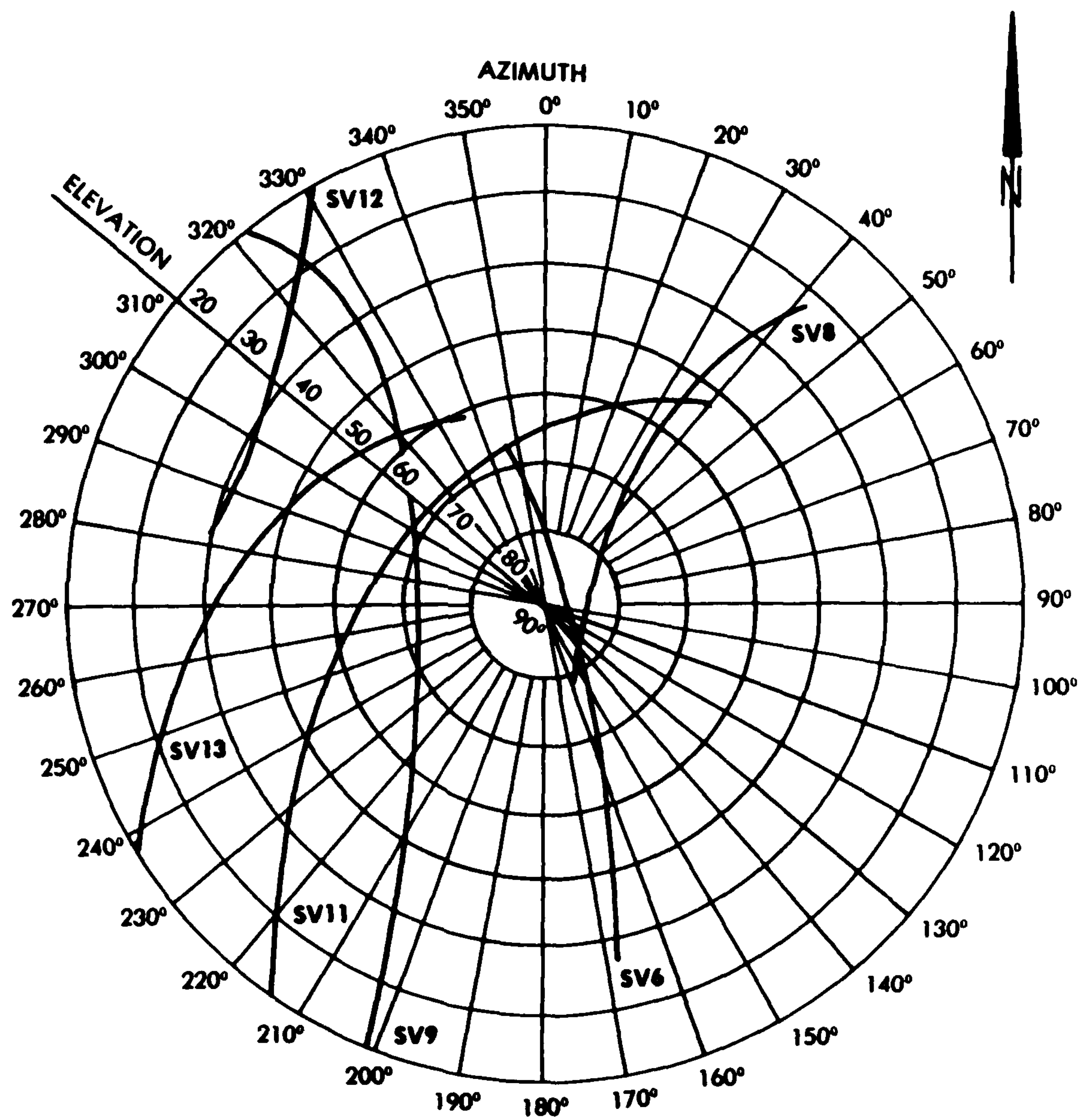
X_i = the i^{th} observation

$\sum_{i=1}^{n}$ = the sum from 1 to n


VECTOR OF APPARENT MOVEMENT
95% ERROR WEDGE
COORDINATE
ERROR ELLIPSE


PC1
PC2
MONITORING MODE
TIMEKEEPING
NETWORK, RECEIVERS, & SATELLITE STATUS
FAILURE RECOVERY
AUTO BOOT LOAD NETWORK DEFINITION
FAILURE RECOVERY
AUTO BOOT LOAD NETWORK DEFINITION
COLLECT MOST RECENT EPOCH FROM NETWORK
DOWNLOAD SEQUENCE
END/BEGIN SESSIONS
DETERMINE IF DATA IS SUFFICIENT
DOWNLOAD EPHEMERIS
CALL UP BASE EPOCH, RUN COMBINED ADJUSTMENT
NETWORK FILE SERVER
FIXED DISK
NETWORK DEFINITION
DEFORMATION ANALYSIS WITH OUTPUT
DUMP RESULTS TO NETWORK
ASSESS & FILTER RAW DATA
ARCHIVE TAPE
USER OPTIONS
I/O DISPLAYS
ANALYSES OF CHOICE
DISPLAY LOGS OF PC1 & PC2
TRIMVEC PROCESSING
PRINTER
PLOTTER
DUMP RESULTS TO NETWORK, DISPLAY ON CRT
UPDATE NETWORK
RESUME LOOPS
AUTOMATIC TAPE ARCHIVING & BACKUP DAILY


RECEIVERS
MODEM/
DATA SWITCH
PC1
(XENIX)
NETWORK
CARD
HARD
DISC
ARCHIVE
TAPE
PRINTER
PLOTTER
PC2
(XENIX)
NETWORK
CARD
MODEM
175 M byte
SYSTEM
DISC
ARCHIVE
TAPE
MODEM
PC3
(XENIX OR DOS)
PRINTER
PLOTTER

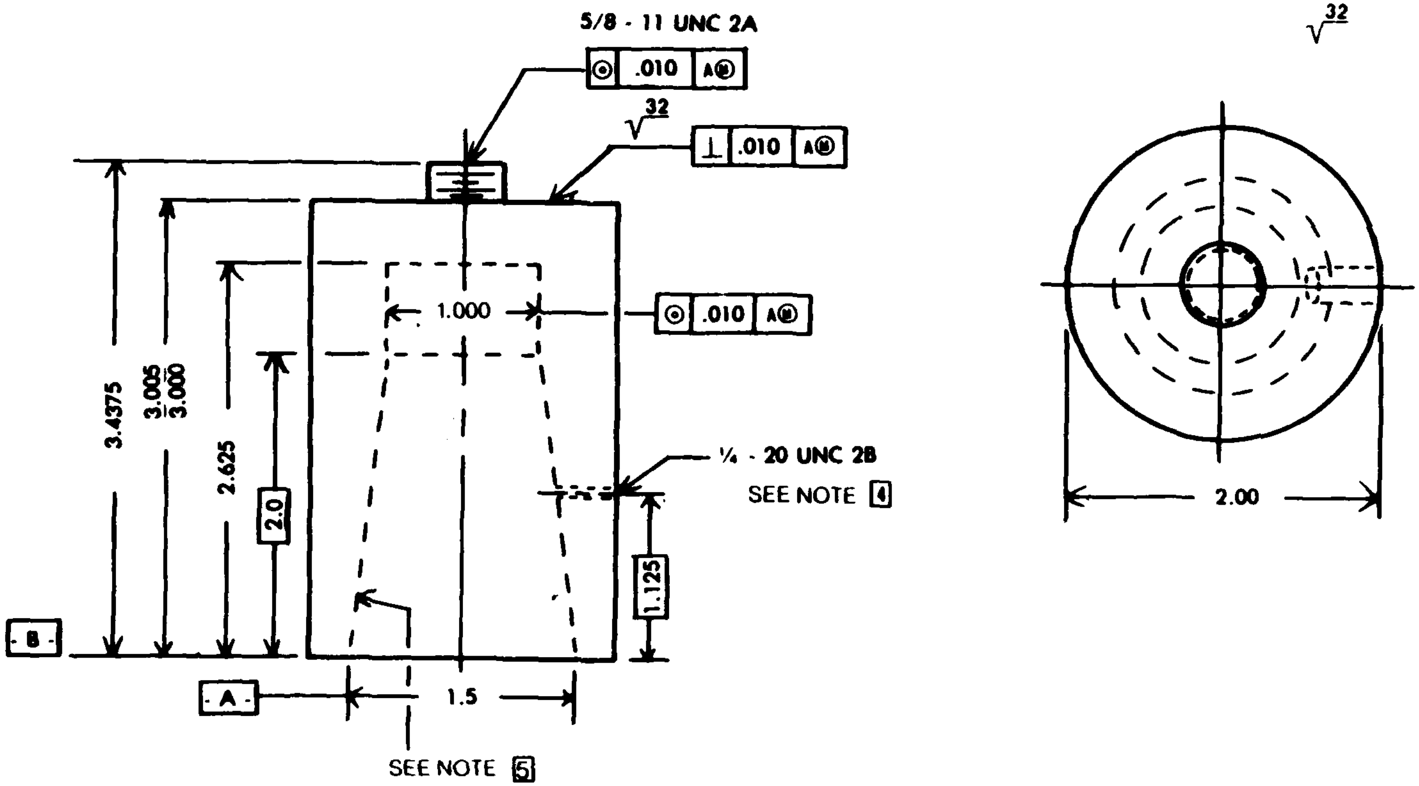

AZIMUTH
ELEVATION
N
SV6
SV8
SV9
SV11
SV12
SV13
0°
10°
20°
30°
40°
50°
60°
70°
80°
90°
100°
110°
120°
130°
140°
150°
160°
170°
180°
190°
200°
210°
220°
230°
240°
250°
260°
270°
280°
290°
300°
310°
320°
330°
340°
350°
20
30
40
50
60
70
80
90°

NOTES:

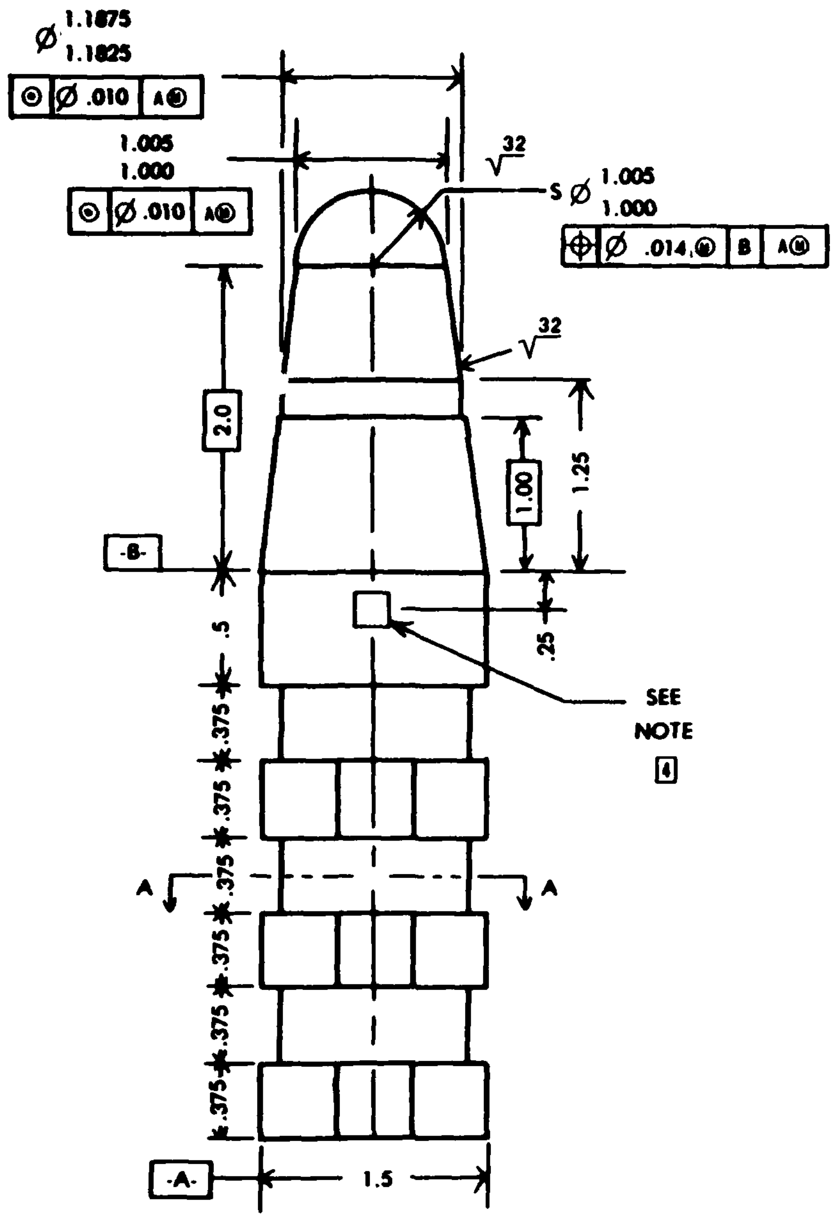
1. DIMENSIONS ARE IN INCHES
2. TOLERANCE ON .xx ± .01, .xxx ± .005
3. TO BE MADE FROM B21 ALLOY - 2" ROUND STOCK

[4] FOR ASSEMBLY - USE ¼-20 UNC-2A, ¼" LONG SET SCREW

[5] ALL MACHINE SURFACES ARE $\sqrt{32}$

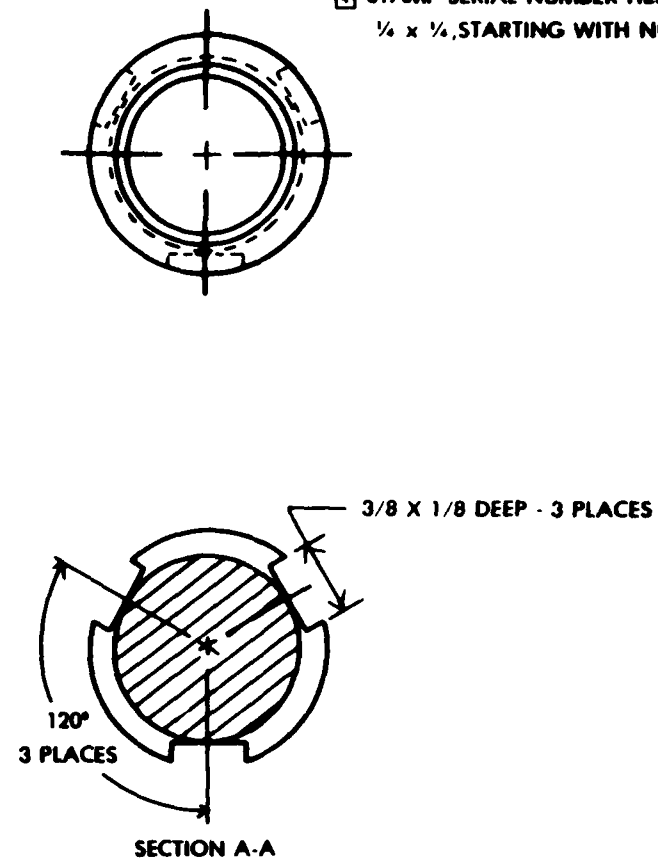


DESIGNED BY MS	FORCED CENTERING DEVICE	U.S. ARMY ENGINEER TOPOGRAPHIC LABORATORIES FT. BELVOIR, VIRGINIA
DATE		
DRAWN BY RW		DRAWING NUMBER
DATE		
APPROVED SRD	SCALE: NONE	ETL CW87-01
DATE 11-12-87		

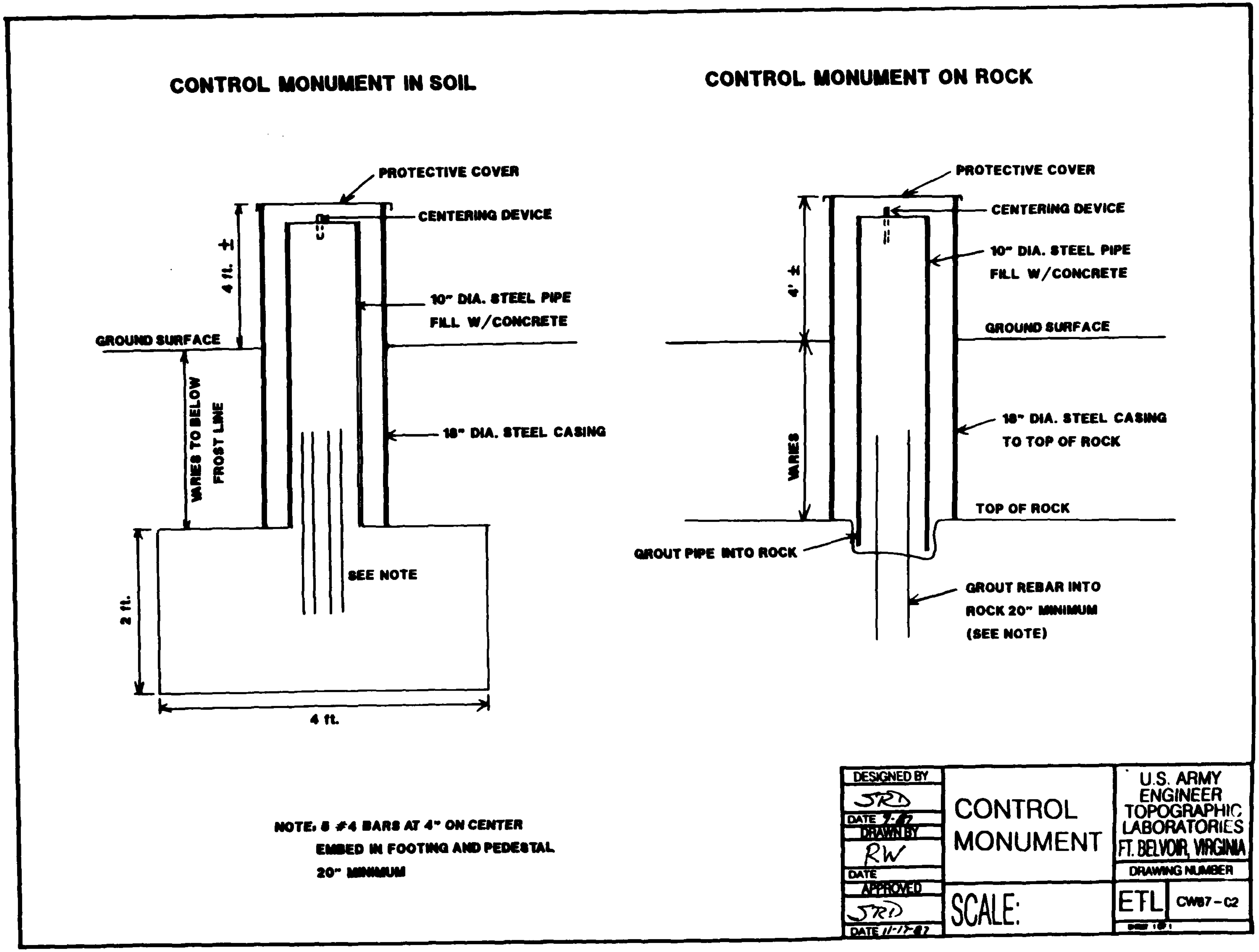


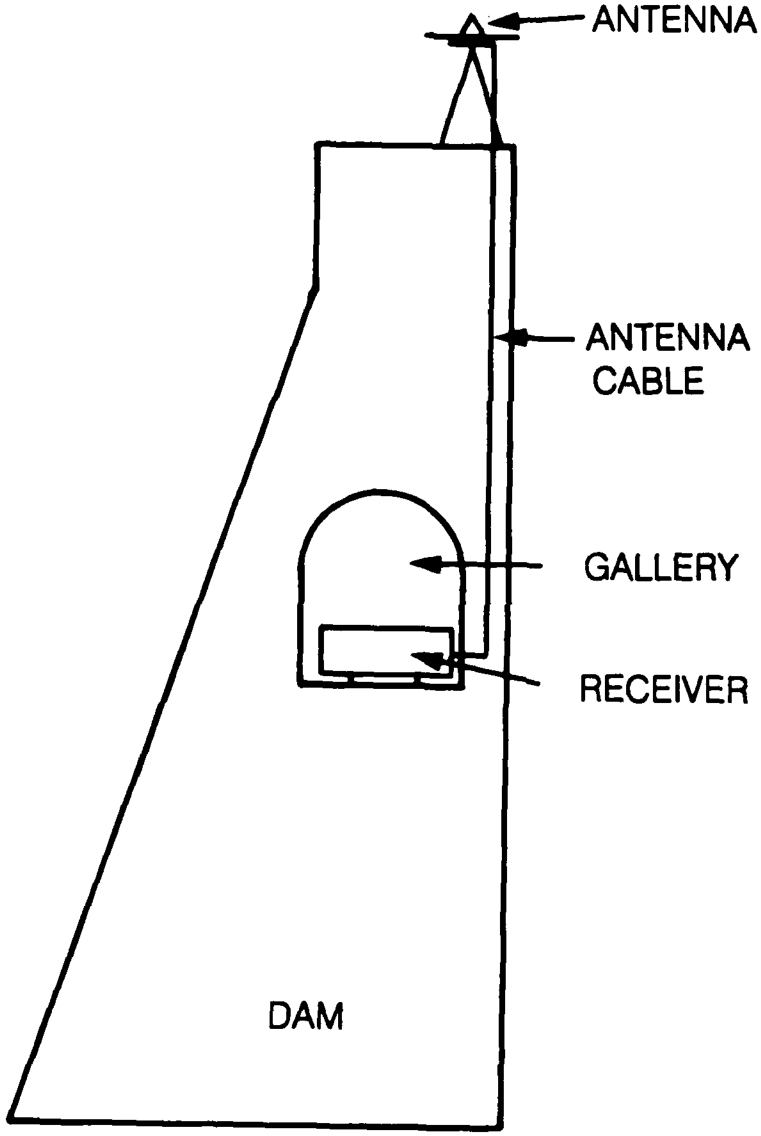
NOTES:

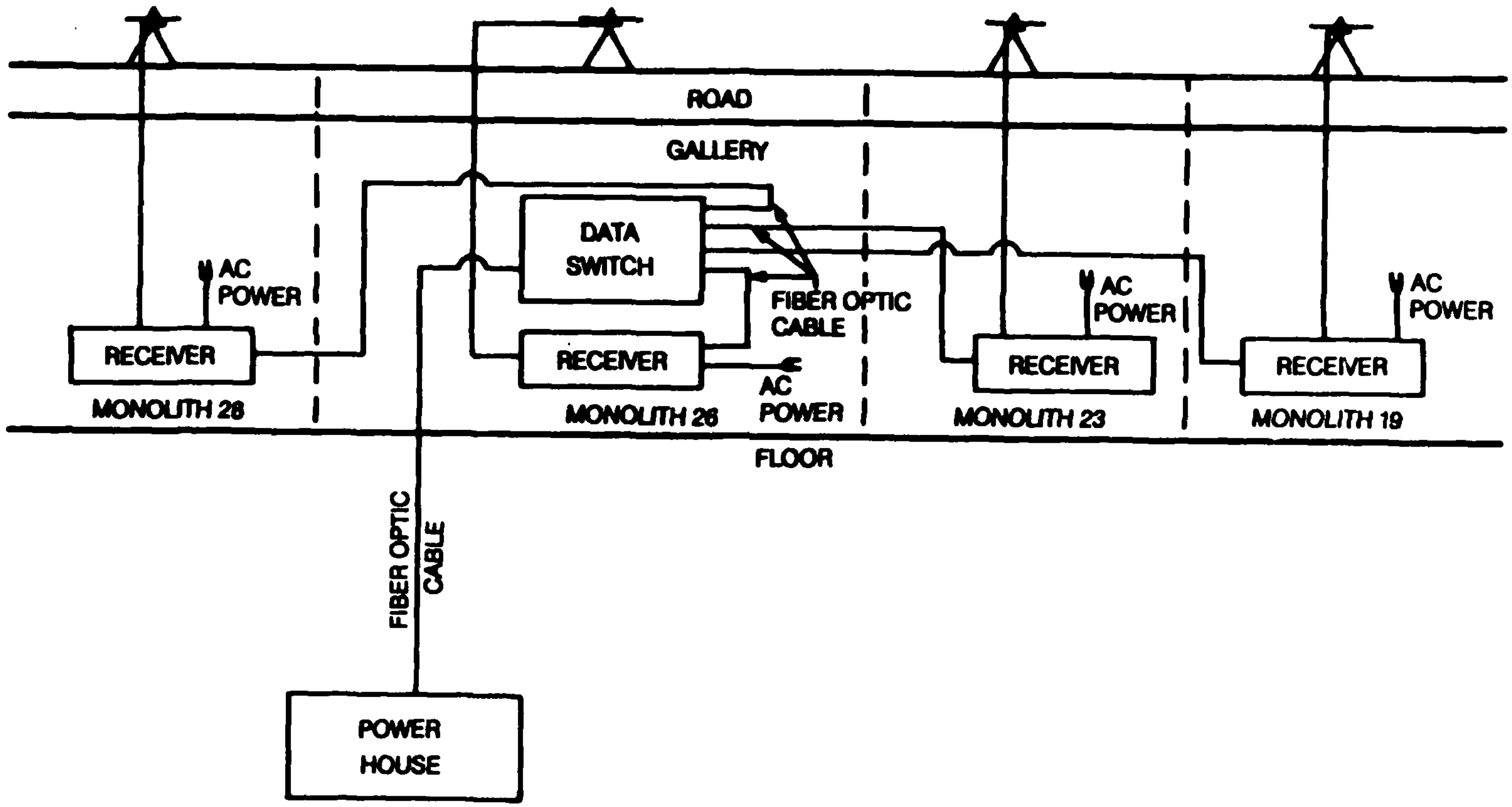
1. DIMENSIONS ARE IN INCHES
2. TOLERANCE ON .xx ± .01, .xxx ± .005
3. TO BE MADE FROM 821 ALLOY 1½ ROD STOCK
4. STAMP SERIAL NUMBER HERE, ¼ x ¼, STARTING WITH NUMBER 1

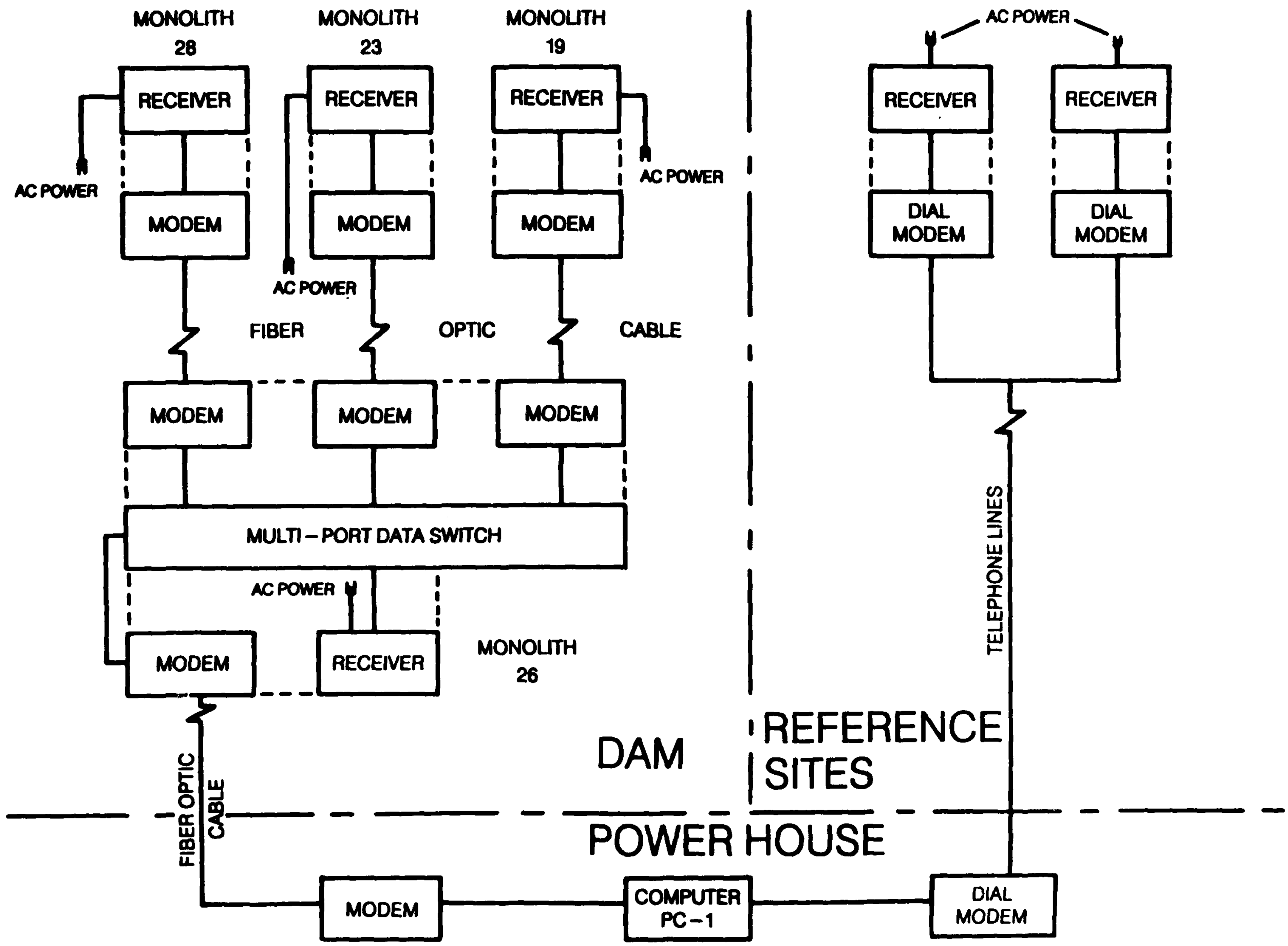


DESIGNED BY MS	FORCED CENTERING DEVICE	U.S. ARMY ENGINEER TOPOGRAPHIC LABORATORIES FT. BELVOIR, VIRGINIA
DATE		DRAWING NUMBER
DRAWN BY RW		
DATE		
APPROVED SRD	SCALE:	ETL CW87-01
DATE 11-12-82		


CONTROL MONUMENT IN SOIL
PROTECTIVE COVER
CENTERING DEVICE
10" DIA. STEEL PIPE
FILL W/CONCRETE
GROUND SURFACE
4 ft. ±
VARIES TO BELOW
FROST LINE
18" DIA. STEEL CASING
SEE NOTE
2 ft.
4 ft.
CONTROL MONUMENT ON ROCK
PROTECTIVE COVER
CENTERING DEVICE
10" DIA. STEEL PIPE
FILL W/CONCRETE
GROUND SURFACE
4' ±
VARIES
18" DIA. STEEL CASING
TO TOP OF ROCK
TOP OF ROCK
GROUT PIPE INTO ROCK
GROUT REBAR INTO
ROCK 20" MINIMUM
(SEE NOTE)
NOTE: 5 #4 BARS AT 4" ON CENTER
EMBED IN FOOTING AND PEDESTAL
20" MINIMUM
DESIGNED BY
JRD
DATE 9-87
DRAWN BY
RW
DATE
APPROVED
JRD
DATE 11-17-87
CONTROL
MONUMENT
SCALE:
U.S. ARMY
ENGINEER
TOPOGRAPHIC
LABORATORIES
FT. BELVOIR, VIRGINIA
DRAWING NUMBER
ETL
CW87-C2


ANTENNA
ANTENNA
CABLE
GALLERY
RECEIVER
DAM


ROAD
GALLERY
FLOOR
RECEIVER
MONOLITH 28
AC POWER
DATA SWITCH
RECEIVER
MONOLITH 26
AC POWER
FIBER OPTIC CABLE
RECEIVER
MONOLITH 23
AC POWER
RECEIVER
MONOLITH 19
AC POWER
FIBER OPTIC CABLE
POWER HOUSE


MONOLITH 28
MONOLITH 23
MONOLITH 19
RECEIVER
RECEIVER
RECEIVER
AC POWER
AC POWER
AC POWER
MODEM
MODEM
MODEM
FIBER
OPTIC
CABLE
MODEM
MODEM
MODEM
MULTI-PORT DATA SWITCH
AC POWER
MODEM
RECEIVER
MONOLITH 26
FIBER OPTIC CABLE
DAM
AC POWER
RECEIVER
RECEIVER
DIAL MODEM
DIAL MODEM
TELEPHONE LINES
REFERENCE SITES
POWER HOUSE
MODEM
COMPUTER PC-1
DIAL MODEM

CAPTIONS

FIG. 1—Vector of Apparent Movement

FIG. 2—Observation and Processing Loops

FIG. 3—Hardware Schemata

FIG. 4—Satellite Visibility Diagram

October 12, 1987

Kansas City, Kansas

FIG. 5—Forced Centering Device: Part 1

FIG. 6—Forced Centering Device: Part 2

FIG. 7—Control Monument

FIG. 8—Dworshak Receiver Installation

FIG. 9—Dworshak Communications: Part 1

FIG. 10—Dworshak Communications: Part 2